IMPACT: International Journal of Research in Engineering & Technology (IMPACT: IJRET)
ISSN (E): 2321-8843; ISSN (P): 2347-4599
Vol. 3, Issue 7, Jul 2015, 63-70

A STATISTICAL ANALYSIS OF JOINT STRENGTH OF DISSIMILAR ALUMINIUM ALLOYS FORMED BY FRICTION STIR WELDING USING TAGUCHI DESIGN APPROACH, ANOVA FOR THE OPTIMIZATION OF PROCESS PARAMETERS

MOHAMMED YUNUS[1] & MOHAMMAD S. ALSOUFI[2]

[1, 2] Department of Mechanical Engineering, Umm Al Qura University, Mecca, Kingdom of Saudi Arabia

ABSTRACT

Friction Stir Welding (FSW) is a solid state joining process, eliminates the drawbacks of common fusion welding are widely used in ship building, aviation and automotive industries. In the present work an attempt has been made to optimize the process parameters of friction stir welding between two dissimilar aluminium alloys (AA7075 and AA6061) to evaluate the output quality characteristics using Taguchi design method. An interaction effect of input parameters is also studied to predict their influence on the output response. Five control factors of mixed levels (2 and 3 levels), L18 orthogonal array are selected to determine the optimum condition for process parameters to improve the performance of FSW. The performance of FSW for dissimilar alloys of aluminium is evaluated in terms of joint's yield strength, Taguchi technique has been employed using orthogonal array, S/N ratio followed by ANOVA (analysis of variance) to study contribution of each parameter and interaction of them on output and confirmation tests at 95 % confidence level to compare with experimental results. Optimal combination of parameters is presented with a good agreement found between the estimated and experimental results within the preferred significant level after verifying experimentally. It was confirmed that Taguchi design method with ANOVA and confirmation tests successfully improved the quality characteristics of yield strength of FSW process.

KEYWORDS: Design of Experiments (DOE), Taguchi Design Method, Signal To Noise (S/N) Ratio, Optimization, FSW, ANOVA, Confirmation Tests

INTRODUCTION

Due to rise of need in recent times for joining material processes to be fast, efficient and environmental friendly, possessing higher mechanical properties such as yield strength, hardness and tensile strength. With the recent advancements in science and technology, Friction stir welding (FSW) has become alternate to the welding process and it is a solid state joining without melting the metal but by using third member as a tool joining two butted faces of similar or dissimilar metals (Roy, R.K et al. 2001). Heat is generated between the metal surfaces and tool leads to very soft region near tool. FSW tool is cylindrical shouldered non consumable with profiled probe like pentagonal, straight and tapered threaded can be fed at constant rate into a butt joint between two butted material. Primarily FSW used on aluminium Al and its alloys but now they are also extended to copper, magnesium and different material combinations.

The advantages of FSW are low defects, free from melt related defects, high joint strength; no filler induced defects, low hydrogen contents. The different types of joint can be produced are butt, corner, lap, T, Spot, Fillet, hem joints, hollow objects such as tanks, tubes, pipes, stocks, of different thicknesses, tapered sections and even 3-D contoured parts.

Most of the present research focuses on similar aluminium sheets FSW and a little work carried on dissimilar

FSW using only aluminium alloys of different grades. To set up an excellent experimental design procedure for Dissimilar FSW a systematic approach on parameter optimization is required. For optimization, Taguchi method followed by ANOVA and confirmation test is used to determine the most influential parameters and predict the best combination of parameters to yield the optimum quality. Only few of similar metals FSW of RDE-40 aluminium alloy and 5086 aluminium plates have successfully analyzed using Taguchi method (A.K. Lakshminarayanan, V. Balasubramanian 2007; Yashar Javadi, Seyedali Sadeghi, Mehdi Ahmadi Najafabadi 2014). In case of dissimilar metals AA2219-AA5083 dissimilar FSW using Taguchi method considering few parameters without ANOVA and confirmation test carried out to optimize the parameters (M. Koilraj, V. Sundareswaran, S. Vijayan, S.R. Koteswara Rao 2012).

In this study, the Taguchi method will be applied on dissimilar FSW of AA6061-AA7075 to predict the optimum parameters and subsequently produce a weld joint with the highest tensile strength value. In this work we have carried out the Taguchi Design method for an optimization of the FSW of dissimilar base metals (AA6061 and AA7075) using process parameters with the determination of most and least significant parameters and to predict optimum yield strength for producing strong FSW joint. In the second stage, effect of each control parameters and interactions between two factors was explored to determine optimal combination with their contribution ratio using ANOVA and confirmation test to assure a good agreement between experiment and estimated values (Mohammed Yunus and Dr. J. Fazlur Rahman 2011).

Taguchi Design Method

Taguchi method is a most powerful and popular statistical method or an approach to provide a new experimental strategy in which a modified and standardized form of design of experiment (DOE) with special application principles. In order to optimize the process/product consisting of number of process parameters, the design of experiments (DOE) can be effectively employed by using number of steps such as planning, conducting and evaluating results of “*Orthogonal Array*” (OA) experiments. Under very noisy environment, the optimum levels of process parameters can be determined. In order to achieve the minimum variance against all variations to produce robust design process and it also focuses on optimizing the quality characteristic of a process economically so that optimal parameter settings of a process with reduced process variability can improve the performance of process. Taguchi’s method involves use of specially constructed consistent “*Orthogonal Array*” (OA) tables for very limited number of experimental trials in designing and easy to apply. Its applications are not only limited to various fields of Engineering and medical, especially in manufacturing industries. To find the significance of usage parameters the following step by step procedure is followed for the DOE [1], [12], [15]

- Define process parameters involved in process.
- Define the level of each process parameters (mixed level in case of different levels).
- Selecting an OA tables to define design of experiment (DOE).
- Conduction of array of experiments by assigning process parameters to columns of OA.
- Analyze the data using S/N ratio and predict the optimum level for better output response.
- Perform verification or confirmation experiment.

EXPERIMENTAL METHODOLOGY

The base materials used in this work are AA 7075 and AA6061 aluminium alloys with thicknesses of 3 mm and 4 mm whose chemical composition is listed in the Table 1. Samples were butt welded using vertical milling machine along the rolling direction, with a rig used is mild steel backing plate to support for base metal during FSW process. A FSW tool with cylindrical taper profile having pin diameter 6 mm and 10° taper, pin length 1.8 mm, and shoulder diameter of 20 mm was chosen for welding. The mechanical properties of the AA 6061 and AA7075 are shown in Table 1. In order to get better material mixing plates are to welded by placing on the advancing side and retreating side alternatively.

Table 1: Chemical Composition of Base Metal Aluminum Alloys (AA 6061 and AA 7075)

Material	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
AA6061	0.550	0.40	0.25	0.535	0.85	0.007	0.20	0.030	97.178
AA7075	0.075	0.28	1.60	0.019	2.30	5.600	0.22	0.028	89.878

In Taguchi design methods, designs of experiments using OA tables make the optimization process to conduct experiments. The results can be transformed into a signal-to-noise (S/N) ratio. Usually, there are three categories of quality characteristic deviating from the desired values by measuring S/N ratio, i.e. the-lower-the-better, the-higher-the-better, and the nominal-the-better [2], [14]. The S/N ratio for each level of process parameters is computed. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of the process parameters is the level with the greatest S/N ratio. Also, analysis of variance (ANOVA) is performed to see which process parameters are most and least significant. The optimal combination of the process parameters can be predicted using S/N and ANOVA analyses. Finally, a confirmation test is conducted to verify the optimal process parameters obtained from the joint's yield strength. Larger-the- better characteristic will be used as higher strength is desired. Table 2 shows the three levels of axial load, rotational speed, welding/transverse speed and forward tilt angle and two levels of thickness of plate leads to mixed level Taguchi design analysis.

Table 2: Process Parameters and Their Levels in Friction Stir Welding

Factor	Parameter	Unit	Level 1	Level 2	Level 3
A	Thickness of plate	Mm	3	4	-
B	Axial Load	KN	2	2.5	3
C	Rotational speed	Rpm	600	900	1200
D	Welding speed	mm/min	75	90	115
E	Tilt angle	degrees	3	4	5

Table 3: Experimental Plan Using an *L*18 Orthogonal Array

S. No.	Thickness of Plate	Axial Load	Rotational Speed (Rpm)	Welding Speed (Mm/Min)	Tilt Angle	Yield Strength	S/N Ratio
1	3	2.0	600	75	3	200	46.0206
2	3	2.5	600	90	4	210	46.4444
3	3	3.0	600	115	5	215	46.8089
4	3	2.0	900	75	4	208	46.3613
5	3	2.5	900	90	5	219	46.8089
6	3	3.0	900	115	3	250	47.9588
7	3	2.0	1200	90	3	220	46.8485
8	3	2.5	1200	115	4	204	46.1926
9	3	3.0	1200	75	5	216	46.6891
10	4	2.0	600	115	5	214	46.6083
11	4	2.5	600	75	3	208	46.3613
12	4	3.0	600	90	4	218	46.7691
13	4	2.0	900	90	5	230	47.2346
14	4	2.5	900	115	3	220	46.8485
15	4	3.0	900	75	4	225	47.0437
16	4	2.0	1200	115	4	210	46.4444
17	4	2.5	1200	75	5	204	46.1926
18	4	3.0	1200	90	3	206	46.2773

RESULTS AND DISCUSSIONS

From the above Table 4 and Figure 1, it is seen that most significant factors can be determined by the larger difference of S/N ratio. The experimental results have been compared with optimal parameters obtained by Taguchi design technique, it is found that most significant parameter that increases yield strength is Rotational speed of the tool (C) followed by Axial Load (B), Welding Speed (D), Tilt Angle (E) and Thickness of plate (A). Interaction between rotational speed and thickness of plate shows they are dependent on each other and are to be considered while varying the thickness of plate. Between the other factors it does not show any significant role for optimization of the process.

Table 4: The Average Response for Signal to Noise Ratio (Larger is the Better)

Level	Thickness Of Plate	Axial Load	Rotational Speed (Rpm)	Welding Speed (Mm/Min)	Tilt Angle
1	215.8	213.7	210.8	210.2	217.3
2	215.0	210.8	225.3	217.2	212.5
3		221.7	210.0	218.8	216.3
Delta	0.8	10.8	15.3	8.7	4.8
Rank	5	2	1	3	4

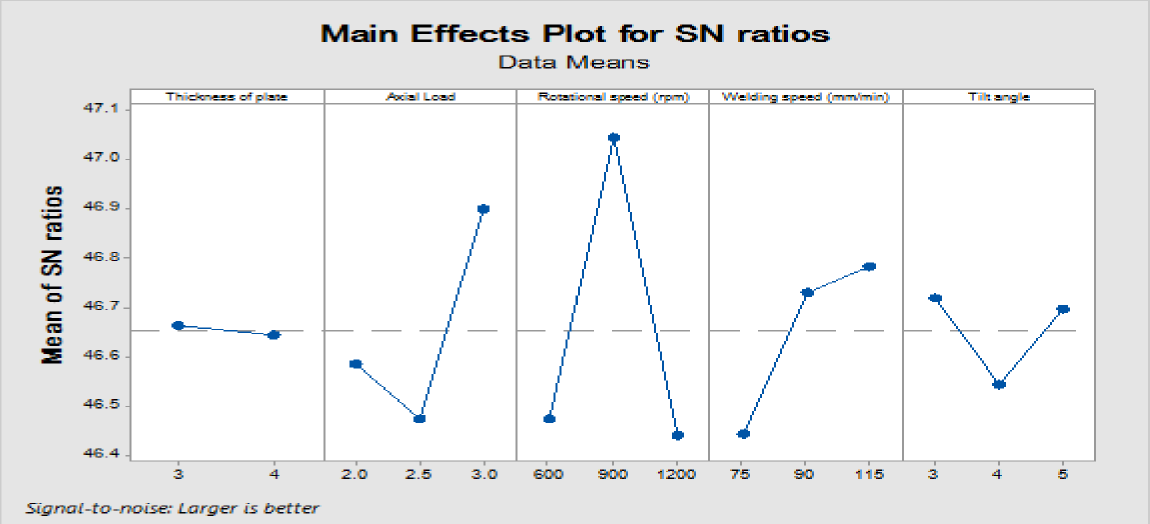

Figure 1: Main Effects Plot for S/N Ratio of Yield Strength

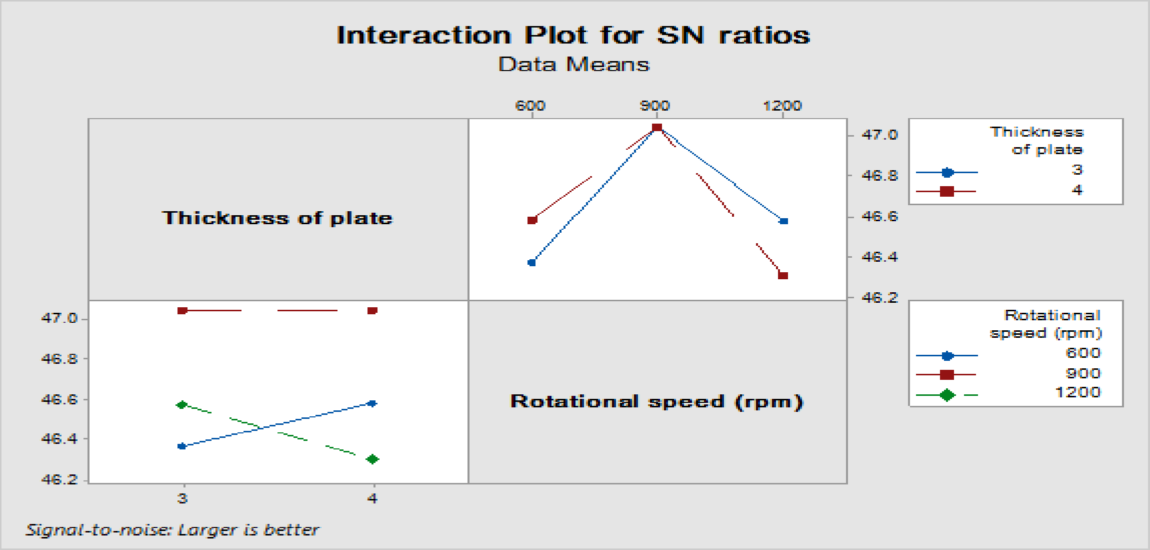

Figure 2: Interaction Plot for S/N Ratio of Yield Strength

Table 5: The Optimal Set of Parameters for Yield Strength of a FSW

Symbols	Parameter	Optimum Setting
A	Thickness of Plate	3 mm
B	Axial Load	3KN
C	Rotational Speed	900 rpm
D	Welding Speed	115 mm/min
E	Tilt Angle	3^0

Analysis of Variance (ANOVA)

ANOVA is used to find the most/major significant parameter which affects the output quality and characteristic using the quantities such as degree of freedom (f), sum of squares (SS), variance (V), percent contribution of each parameter (F-ratio) and P-values are determined. From the Table 5 it is observed that highest F-ratio or lowest P-value which indicates most significant parameter is Rotational speed of the tool (C), least significant factor is the Thickness of plate (A) and Axial Load (B), Welding Speed (D), Tilt Angle (E) and have moderate value between the other two. In case of interaction between the two factors, AXB also seen as third significant factor affecting the process not as a whole but under the variation of thickness of plate. Interaction other factors does not affect the optimum combination of process parameters in optimization process.

Model Summary

S = 8.93340 R-sq = 86.31% R-sq (adj) = 41.83%

Table 6: Analysis of Variance Results for Yield Strength of a FSW

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution Ratio
Thickness of plate	1	6.72	6.722	0.08	0.786	0.667
Axial Load	2	430.78	215.389	2.70	0.181	22.81
Rotational speed (rpm)	2	857.44	428.722	5.37	0.074	45.51
Welding speed (mm/min)	2	171.50	85.750	1.07	0.423	9.1
Tilt angle	2	63.17	31.583	0.40	0.697	3.39
Thickness of plate*Axial Load	2	266.78	133.389	1.67	0.297	14.15
Thickness of plate Rotational speed (rpm)	2	80.78	40.389	0.51	0.637	5.4
Error	4	319.22	79.806			
Total	17	2332.28				

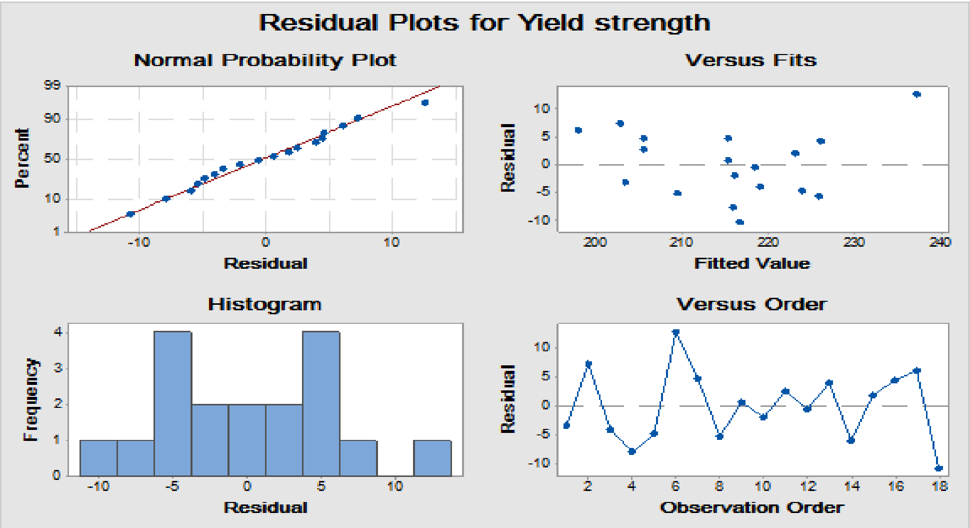

Figure 3: Residual Plots for Yield Strength of a FSW Joint in ANOVA

Confirmation Test:

For the verification of results the confirmation test is conducted [15] and an optimum condition at the selected levels of significant parameters can be predicted such as A2, B3, C2, D1, E1 and F3. The final optimal set of combination of parameters is found out. The predicted average (M) of the response shrinkage of mold can be expressed as [14], [19].

$$M = (A1-T) + (B3-T) + (C2-T) + (D3-T) + (E1-T) + T$$

Where, T = overall average of S/N ratio.

$M = (47.04826 - 46.66183) + (46.8978 - 46.66183) + (46.7835 - 46.66183) + (46.7192 - 46.66183) + (46.6636 - 46.66183) + 46.66183 = 47.46504$ dB. Using

$$N_f = \frac{Number\ of\ Trials}{1 + Total\ DoF\ of\ total\ number\ of\ factors} = \frac{18}{1+17}$$

And R = number of trials to run confirmation test, variance and degree of freedom of error from ANOVA table and $F\alpha\ (1, 4) = 7.71$ at 95 % confidence level and tabulated, a confidence interval (C.I) is evaluated = 0.34. At the 95 % confidence level the estimated / predicted average of the shrinkage found to be in the range of 47.12504 dB < Yield strength > 47.80504 dB.

Table 7: The Comparison of Estimated and Experimental Results of Yield Strength

Particulars	Optimum Level		
	Estimation	**Experimental**	**Difference**
Level	$A_1B_3C_2D_3E_1$	$A_1B_3C_2D_3E_1$	-
Yield Strength in MPa	232.006	240.713	8.707
S/N Ratio in dB	47.31	47.63	0.32

CONCLUSIONS

In this paper, optimization of process parameters of friction stir welding for joining two dissimilar metals have been carried out using Taguchi design method followed by ANOVA and confirmation test. From the analysis of the Taguchi design approach, the following can be concluded from the present work:

- The optimum conditions for mechanical yield strength are A1, B3, C2, D3, E1, i.e., Rotational speed of the tool (900 rpm) followed by Axial Load (3 KN), Welding Speed (115 mm/min), Tilt Angle (3^0) and Thickness of plate (3 mm).
- The optimum yield strength can be obtained is 241 MPa with rotating speed of tool as the most significant factor while the thickness of plate as the least significant factor in affecting FSW strength.
- From ANOVA results, the contribution ratio of each parameter indicates that rotational speed is major significant factor and thickness of plate is minor significant factor. Interaction between the factors has been found no major affect on the output quality.
- The estimated range for optimum shrinkage is 47.12504 dB < yield strength > 47.80504 dB. The experimental results are found in good agreement within the specified range.
- It is also noticed that, there was a good agreement between predicted and the actual values in respect of yield strength within the preferred significant level.
- Hence, by controlling the rotational speed, we can obtain very good FSW components of higher yield strength.

REFERENCES

1. Roy, R.K., 2001, *Design of Experiments using The Taguchi Approach: 16 Steps to Product and Process Improvement, John Wiley & Sons, Inc*.
2. T. Sakiyama, G. Murayama, Y. Naito, K. Saita, Y. Miyazaki, H. Oikawa, T. Nose, *Dissimilar Metal Joining Technologies for Steel Sheet and Aluminum Alloy Sheet in Auto Body, Nippon Steel Technical Report (2013), Pp.* 91-98.
3. W. M. U. Thomas, E. D. Nicholas, *Friction stir welding for the transportation industries, Material Design*, 18 (1998), Pp. 269-273.
4. J. F. Guo, H. C. Chen, C. N. Sun, G. Bi, Z. Sun, J. Wei, *Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters, Material Design*, 56 (2014), Pp. 185–192.
5. P. Cavaliere, *Friction Stir Welding of Al Alloys: Analysis of Processing Parameters Affecting Mechanical Behavior, Procedia CIRP 11*, (2013), Pp. 139–144.
6. B. T. Gibson, D. H. Lammlein, T. J. Prater, W. R. Longhurst, C. D. Cox, M. C. Ballun, K. J. Dharmaraj, G. E. Cook, A. M. Strauss, *Friction stir welding: Process, automation, and control*, Journal of Manufacturing Process. (2013) Pp. 1–18.
7. A.K. Lakshminarayanan, V. Balasubramanian, *Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique, T. Nonferr. Metal Soc.* 18 (2007), Pp. 548-554.
8. Yashar Javadi, Seyedali Sadeghi, Mehdi Ahmadi Najafabadi, *Taguchi optimization and ultrasonic measurement of residual stresses in the friction stir welding, Material Design*, 55 (2014), Pp. 27-34.
9. M. Koilraj, V. Sundareswaran, S. Vijayan, S.R. Koteswara Rao, *Friction stir welding of dissimilar aluminium alloys AA2219 to AA5083 – Optimization of process parameters using Taguchi technique, Material Design*, 42 (2012), Pp. 1-7.
10. R. S. Mishra, Z. Y. Ma, *Friction stir welding and processing, Mater. Sci. Eng. R*. 50 (2005), Pp. 1-78.
11. P. Cavaliere, A. Squillace, F. Panella, *Effect of welding parameters on mechanical and micro structural properties of AA6082 joints produced by friction stir welding, J. Mater. Process. Technol.*, 200 (2008), Pp.364372.
12. Lin T. R. et al., *Optimization technique for face milling stainless steel with multiple performance characteristics, Int. J Adv Manufacturing Technology*, Volume 19, 330 (2002).
13. P. Sharma, A. Verma, R.K. Sidhu, O.P. Pandey, *Process parameter selection for strontium ferrite sintered magnets using Taguchi L9 orthogonal design, Journal of Materials Processing Technology*, 168 (2005), Pp. 147-151.
14. Hari singh, Pradeep Kumar, *Tool wear optimization in turning operation by Taguchi method", Indian Journal of Engineering and Material Sciences*, Volume 11, February 2004, Pp. 19-24.
15. Mohammed Yunus and Dr. J. Fazlur Rahman, *Optimization of usage parameters of ceramic coatings in high temperature applications using Taguchi design, International Journal of Engineering Science and Technology*

(IJEST), Vol. 3 No. 8 August 2011, Pp. 6364–6371.

16. Y.D.Sato & H.Kokawa., 2003, *Friction stir welding (FSW) process*, *Welding International*, 17 (11), Pp.852-853.
17. Terry Khalid., 2005, *An outsider looks at friction stir welding, Report #ANM-112N-05*.
18. P. L. Threadgill., 2007, *Terminology in friction stir welding, Science and Technology of Welding and Joining*, Vol 12, No 4357, 360.
19. R.S. Mishra, Z.Y. Ma., 2005, *Friction stir welding and processing, Materials Science and Engineering*, R 50, Pp.1–78.
20. M. Kumagai., 2003, *Recent technological developments in welding of Aluminium and its alloys, Welding International*, 17 (3), Pp.173-181.